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ENERGY DISSIPATION CHARACTERISTICS IN TISSUE FOR PROTON RADIATION IN SPACE
I. COMPARATIVE ANALYSIS OF THE LET SPECTRA OF MONOENERGETIC, FLARE PRODUCED, AND FISSION NEUTRON RECOIL PROTONS

By

Hermann J. Schaefer

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Research Report

ENERGY DISSIPATION CHARACTERISTICS IN TISSUE FOR PROTON RADIATION IN SPACE
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Hermann J. Schaefer

Bureau of Medicine and Surgery
Project MR005.13-1002
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SUMMARY PAGE

.ET (Linear Energy Transfer) for different types and
s a mean value and does not convey much information
which is, even for a monoenergetic beam of one type
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ndard x-rays can be obtained by comparing the LET
LET spectrum of a radiation requires a complete follow-
ıal energy transfers including all secondaries of the
ı an energy level of 100 e-volts.

e first results of a theoretical study aimed at a full
typical space radiation proton beams and their transitions
ıpact absorbers. The data are limited to the LET spectrum
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Space flight - Radiation hazard in

Protons - Energy

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3

INTRODUCTION

Accurate assessment of the radiation exposure in proton radiation fields in space cannot be based solely on a determination of the tissue ionization dosage in rad, but requires in addition information on the RBE (Relative Biological Effectiveness). Since the radiation load in a human target in flight through the Van Allen Belt or through a solar proton beam can easily reach the level of acute injury, the rem doses involved, i.e., the local RBE in tissue, should be determined as precisely as possible. This is a complex task because the energy spectrum of the proton radiations in question is extremely heterogeneous and undergoes continuous changes as the radiation penetrates more deeply into the target.

Of a more principal nature is the difficulty arising from the fact that the RBE is an artificial concept greatly oversimplifying the relationships which govern the action of ionizing radiation on living matter. As a consequence, no general, well-defined values for the RBE of various types of ionizing radiations at various energy levels can be established beyond the broad statement that the RBE seems directly related to the LET (Linear Energy Transfer) of the ionizing particles involved. LET as a purely physical quantity has the advantage that it is rigorously defined and therefore serves well as a criterion for characterizing and distinguishing different types of radiations. Ultimately, of course, the RBE cannot be dispensed with if absorbed energy is to be expressed in terms of rem dose. However, analysis of the LET spectrum of a radiation of unknown RBE and comparison to the corresponding spectrum of standard x-rays can allow specific conclusions concerning the relative biological effectiveness without the latter being formally expressed as a numerical factor. The following treatise discusses these aspects for flare produced protons as compared to monoenergetic and neutron recoil protons.

MEAN LET VERSUS LET SPECTRUM FOR PROTONS

The strong dependence of RBE on energy for protons and heavier nuclei has been recognized for a long time. In two sets of classical experiments, using protons, deuterons, and alpha particles from the Berkeley cyclotron, Tobias and co-workers (1) and von Sallmann, Tobias, and co-workers (2) demonstrated the basic difference in the RBE of particles in the energy range of several hundred Mev where the LET is low as compared to the terminal sections of the tracks of these particles corresponding to energies of a few Mev where the LET is high. Because of the low penetrating power of protons of the latter type, it is experimentally much easier to produce them indirectly as recoil protons within the specimen by means of neutron irradiation. With regard to RBE values obtained with this particular method the reader is referred to the comprehensive studies of Conger, Randolph, Sheppard, and Luippold (3) on chromosomal damage in Tradescantia and of Storer, Harris, Furchner, and Langham (4) on acute effects in mammalian systems.

On the basis of a critical evaluation of all available experimental information on the LET/RBE relationship and with the express intention of providing a safety margin from a radiation protection standpoint, the National Committee on Radiation Protection (5) has recommended certain RBE values for given LET intervals. In a previous study (6) an attempt has been made to establish, on the basis of these official recommendations, mean RBE values for the local ionization dosages in a human target exposed to typical proton beams in space. Quite obviously this approach leaves much to be desired from a scientific standpoint. A basic objection against it derives from the fact that the LET as commonly quoted for any type of ionizing radiation merely denotes the total energy dissipated per unit length of path, yet does not convey any information on the actual spacing of the ionization events in the microstructure of the irradiated tissue. Though this is a well-known fact, Table I describes it in more detail. In the first column selected kinetic energies of protons are listed. The second column shows the corresponding LET, the third column the maximum transferable energy to electrons, and the fourth column the range in tissue for these electrons.

Table I

Energy Dissipation Characteristics of Protons

Protons		First Order Secondary Electrons	
Kinetic Energy Mev	LET k ev/Micron Tissue	Max. Trans. Energy, Mev	Range in Tissue, Micron
100	0.635	0.231	556
50	1.08	0.113	172
10	3.95	0.022	10
1	21.35	0.0022	0.18

It is immediately seen that the distances over which the dissipated energy is actually spread are, for higher energies, considerably larger than one micron. For a true description of the energy dissipation, therefore, it will be necessary to carry out a complete analysis of the entire chain of events tracking down all secondaries until they come to rest. This leads to an LET spectrum rather than to a single LET value.

It has been generally accepted in this type of analysis to consider an energy transfer to a secondary electron as local if an energy exchange of 100 e-volts or less is involved. The range of a 100 e-volt electron in tissue equals 0.003 micron or 30 AU (1 Angstrom Unit = 10^{-7} millimeter). The computational procedure of establishing the LET spectrum for any type of radiation is very complex. The existing literature on this particular problem has been listed in an earlier report (7). In the same reference, a brief recapitulation of the basic steps in analyzing the LET distribution of a given radiation has been given. For a more detailed introduction to the subject, the study of Burch (8) is especially recommended.

In analyzing LET spectra of proton beams in space one issue is of particular importance. It concerns the ranges in tissue along which a proton or electron of a certain energy maintains its local LET. The upper curve in Figure 1 shows the local LET of protons and the lower one that of electrons as a function of residual range.

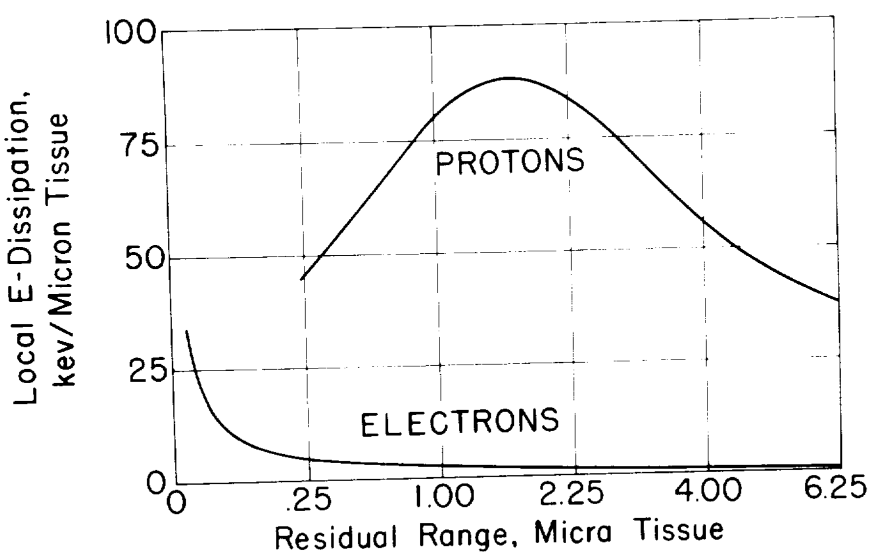

Figure 1

Local Energy Dissipation of Protons and Electrons in the Terminal Sections of Their Paths in Tissue

Abscissa scale is quadratic for increasing resolution toward zero. Ordinate shows fraction of total energy dissipation comprising events transferring less than 100 e-volts.

It is seen that a proton maintains peak values of the local LET over distances of several micra in tissue whereas an electron does so only for some 40 or 50 millimicra (400 or 500 AU). If we assume that production of radiation damage in sensitive centers in the tissue fine structure requires penetration by an ionization column of at least several hundred AU length, the effectiveness of protons, i.e., the RBE, should be substantially greater than of electrons. This is in agreement with the experiment. It has been shown that photoelectrons of 1.3 kev are almost without effect in causing chromatid breaks due to their short range which renders them incapable of crossing the chromatid thread of about 1000 AU diameter. It is seen, then, that the concept of local energy dissipation, though it describes the microstructural distribution of dose much more accurately than the mean LET, has a severe limitation concerning those high LET values which are sustained only over very short distances. It is not within the scope of this treatise to discuss the microbiological significance of this difference in more detail. The reader is referred to the reviewing articles of Hutchinson (9), Howard-Flanders (10), and Hutchinson and Pollard (11). In the present context, only one consequence is of importance. In establishing the LET spectra for protons in the energy interval below 1 Mev, where the local LET of the primary proton itself becomes equal to the maximum at the upper end of the LET spectrum of the electrons, the two contributions should not be added because they represent basically different types of radiation exposure for the reasons just explained. Figure 2 illustrates this graphically. Shown at the left is the LET spectrum of 20 Mev protons and at the right that of 0.5 Mev protons. The tall narrow columns represent, for both energies, the local energy dissipation of the parent proton itself, i.e., the energy imparted by the proton to electrons in so-called soft collisions in which the energy transfer does not exceed 100 e-volts. It is seen that this contribution coincides, for 0.5 Mev, with the peak LET of the secondary electrons from hard collisions. However, for the reasons explained above, these two contributions cannot be considered equivalent with regard to their LET and therefore cannot be consolidated into one spectrum.

In view of the unique characteristics of the energy dissipated by the primary proton itself in soft collisions, it seems of interest to determine what percentage of the total energy dissipation it represents. This relationship is shown in Figure 3 as a function of kinetic energy of the primary proton. It is seen that the fraction equals 100 per cent at very low energies, then drops, but levels off soon to a constant value of about 65 per cent. Expressed in terms of Figure 2, this means that the energy represented by the areas of the narrow columns equals 65 per cent of the total shaded area in each graph. In other words, about two thirds of the local energy dissipation of protons are due to primary collisions of the parent particle itself.

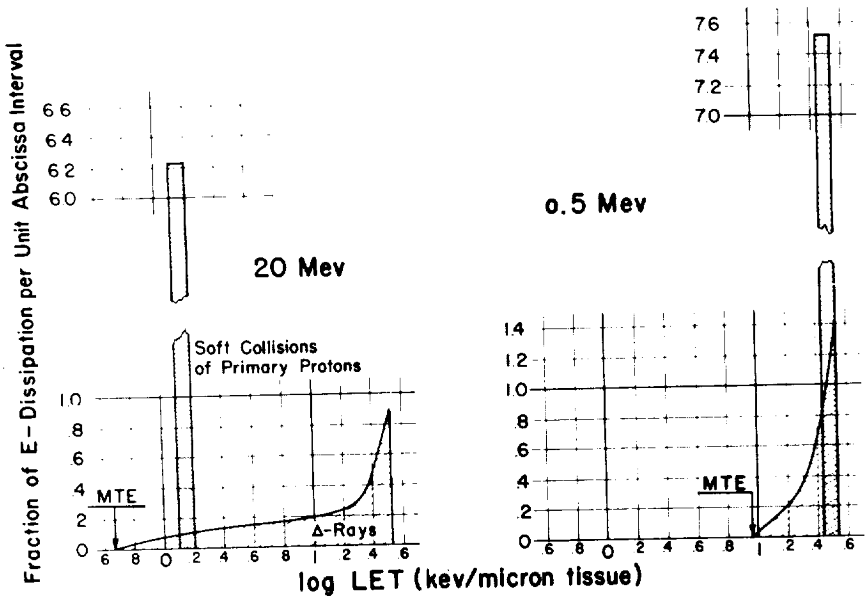

Figure 2

LET Spectra for 20 Mev and 0.5 Mev Protons

Arrow at MTE indicates initial value of local E-dissipation of first order secondary electrons receiving Maximum Transferable Energy. Total shaded area in each graph equals one unit square (25 small squares).

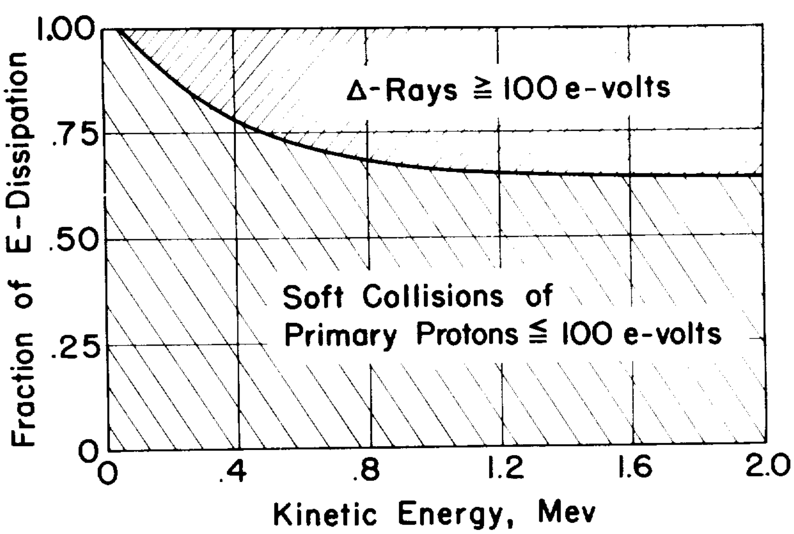

Figure 3

Relative Shares of "Hard" and "Soft" Collisions in Energy Dissipation of Protons

LET SPECTRA OF FLARE PRODUCED AND FISSION NEUTRON RECOIL PROTONS

Proceeding from monoenergetic protons to beams with continuous energy spectra, the LET analysis requires an additional step. The total energy range of the spectrum has to be broken down into intervals narrow enough to be treated as monoenergetic, the LET distribution for each interval has to be established, and a numerical integration has to be carried out over all contributions, each weighted according to its differential particle intensity in the energy spectrum. As explained in the preceding section, the energy contributions from hard collisions have to be carried separately in this evaluation since they originate from electrons and are essentially equivalent, in their relative biological effectiveness, to electrons from x-rays. As far as an increased RBE is concerned, the specifically important quantity in the LET spectrum of protons is the contributions from soft collisions. It was shown in Figure 2 that these contributions show, for monoenergetic protons, a very narrow LET distribution. In fact, if straggling is disregarded, they would be monochromatic in LET. For a heterogeneous energy spectrum, however, the contributions from different energy intervals spread over a wide LET continuum. This continuum is the relevant quantity in a comparative evaluation of RBE and should be plotted without the LET spectrum of delta ray contributions. The top and center graph in Figure 4 show such LET spectra for a flare produced proton beam after it

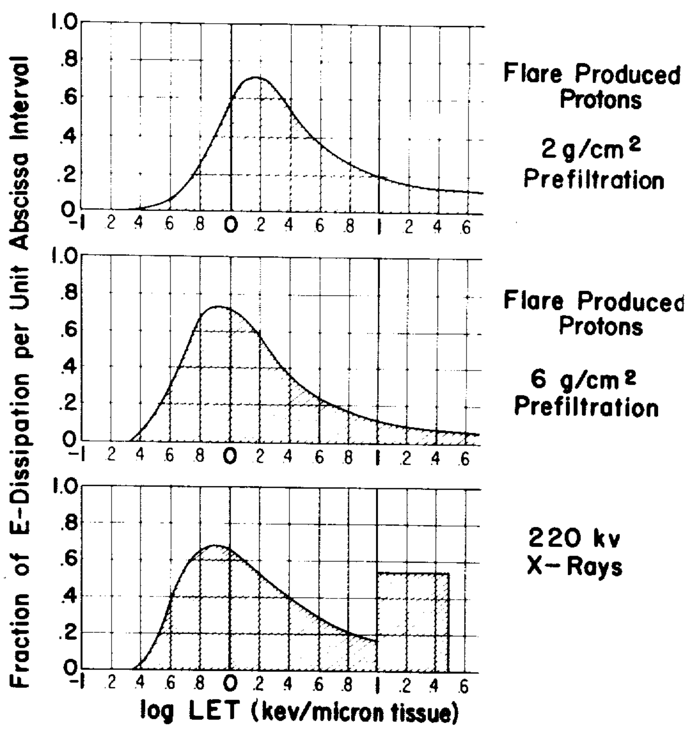

Figure 4

Differential LET Spectra for Flare Produced Protons After Passing Through 2 g/cm^2 (Top) and 6 g/cm^2 (Center) Organic Material and for Standard X-Rays (Bottom) has travelled through 2 g/cm^2 (top) and 6 g/cm^2 (center) organic material. They are aligned with a bottom graph showing the LET spectrum for 220 kv x-rays as computed by Cormack and Johns (12). The square shaped area above log LET = 1.0 in this spectrum is an artifact. Since the mechanism of energy dissipation for electrons below 1 kev is incompletely understood, the authors have indicated this fraction of the energy dissipation merely by its correct relative amount, i.e., by the corresponding area. Here again, it might be emphasized that this particular fraction, even if it is merely considered by its integral area, allows no comparison to corresponding areas in proton spectra because of the differences in length over which the ion columns are sustained.

The most interesting feature of Figure 4 is the striking similarity between the flare proton spectra and that of standard x-rays. Figure 4 shows that the bulk of energy dissipation in all three spectra takes place at LET values below the 10 kev/micron limit and that the configuration of the three spectra in this region is quite similar. It is quite obvious that the ionization dosages represented by these sections of the proton spectra are equivalent to x-ray dosages and therefore have to be assigned the RBE of 1.0.

The sections beyond the just mentioned limit represent, in the proton spectra, energy dissipation to which RBE values greater than 1.0 would belong. Just what specific values should be chosen is a problematic issue. One has to realize that a radiation which produces ionization in tissue at strictly one LET or at least at values in a narrow LET interval simply does not exist. Consequently, experimental data on RBE factors for "monochromatic" LET values are not available. The closest approach seems to be the investigation of Conger and co-workers quoted above. At least, these authors have given most careful consideration to the limitation under discussion. They arrive at an RBE/LET relationship which is shown in the upper graph of Figure 5. It is seen that the critical interval of a steep rise of the RBE starts slightly below the log LET = 1.0 limit. It might be mentioned that the data of Conger and co-workers shown in the upper graph of Figure 5 pertain to cytological damage in Tradescantia. The data of Storer and co-workers indicate that the RBE for acute damage in mammalian systems seems to be somewhat smaller. It would be erroneous, however, to invoke this fact as proof that the RBE relationship of Figure 5 contains a safety margin if used for a determination of rem doses for man. Chromosomal damage identified in individual cells is a much more sensitive reaction than the more complex end effects used as criteria in Storer's investigations. It seems advisable, therefore, to base computations of rem doses strictly on the upper graph of Figure 5.

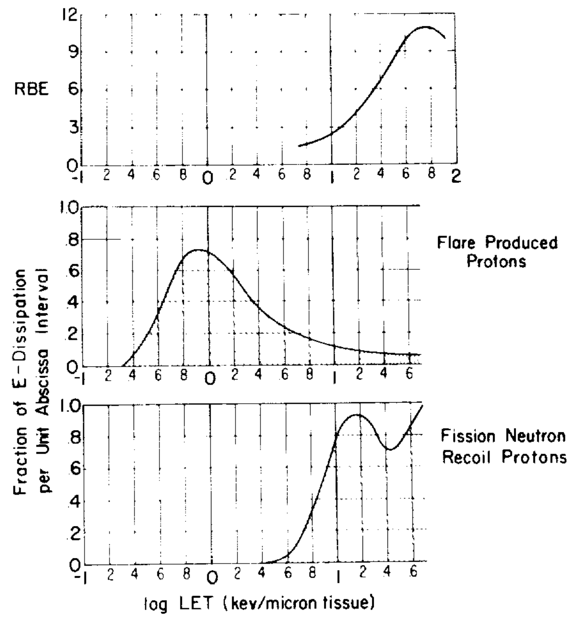

Figure 5

LET Spectra of Flare Produced Protons (Center) and of Neutron Recoil Protons from Thermal Fission (Bottom) Aligned with RBE (Top)

It is of particular interest to compare the RBE/LET curve under discussion as well as the LET spectrum of flare produced protons to the LET spectrum of fission neutron recoil protons. As is well known, the Code of Federal Regulations (13) has assigned to the latter type of proton radiation an RBE of 10. The bottom graph in Figure 5 shows the LET spectrum of such protons. It is seen that the entire energy dissipation takes place at LET values to which elevated RBE values would have to be assigned. The profound difference between flare produced and fission neutron recoil protons could not be better demonstrated than by this comparison of their respective LET spectra.

CONCLUSIONS

The graphs of Figure 5 delineate the dose fraction of flare produced protons to which RBE values larger than 1.0 would have to be applied. The results of a more detailed computation of pertinent rem doses have been presented in the earlier report(7). As shown there, the rem dose reaches, for a prefiltration of 2 g/cm^2, a highest value of 13 per cent of the total rem dose. This maximum always occurs in the surface layer of the target. Since the earlier study appeared, the National Committee on Radiation Protection and Measurements (14) has defined a new term, the ERD (Equivalent Residual

Dose), proposing an equation for its computation which assumes, for injury from acute exposures, an irreparable fraction of 10 per cent and a recovery half-time of one month for the remaining 90 per cent. This equation is a compromise reflecting well the existing experimental information on what has been called so far, in radiobiological literature, "net injury" or "residual injury" or "net exposure status." The ERD as conceived by the NCRPM is intended as a guideline for action during the "reconstruction phase after a nuclear attack," and is not a "reliable predictor of any of the late somatic effects of radiation or of the genetic effects." The NCRPM also expressly states that it is not recommended to extend the "calculation beyond one year." Emphasizing the just mentioned restrictions, NASA has adopted the concept of the ERD and the equation as proposed by the NCRPM for assessing the exposure status of astronauts (15) as far as acute radiation sickness during a mission is concerned. This has, of course, no bearing on the problem of how to determine the accumulated ERD for repeated missions or for the entire career of an astronaut. Obviously, for the latter determination late damage such as life shortening should also be considered. In this respect, the findings of the present study seem to have special significance. As pointed out earlier (7, 14), experimental evidence indicates that, for late damage, exposure to high-LET radiation shows a smaller recovery factor than exposure to x- or gamma rays. Though the available data do not yet allow establishing a concise numerical formula for the corresponding ERD, it seems advisable that the high-LET fraction of a proton exposure be entered separately into the computation with an RBE of 10 and with no or a greatly reduced recovery allowance. The implementation of this precept would require a dosimetric device which can discriminate LET in recording ionization dose. The design of such an instrument, which should at the same time be direct reading, sturdy, and of small size and weight, seems to pose some difficulties especially if the comparatively high dose rates involved are considered. Since deep space ventures with man-carrying vehicles are in the advanced planning stage, high priority should be assigned to this instrumentation problem.

12

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